RESEARCH HIGHLIGHTS: June 1990 - May 1991

BAROCLINIC FLOWS AND BAROCLINIC CHAOS

Linear instability calculations by Dr. T. Miller at MSFC have suggested that the GFFC should exhibit classic baroclinic instability at accessible parameter settings. Of interest are the mechanisms of transition to temporal chaos and the evolution of spatio-temporal chaos. In order to understand more about such transitions we have conducted high resolution numerical experiments for the physically simplest model of two layer baroclinic instabitity. This model has the advantage that the numerical code is exponentially convergent and can be efficiently run for very long times, enabling the study of chaotic attractors without the often devastating effects of low-order trunction found in many previous studies.

Cattaneo and Hart (1990) showed that there are a countable infinity of invariant manifolds in spectral space. This means that for a given set of external parameters that there are potentially an infinity of possible distinct statistical equilibria. In practice most of these are unstable, but numerical studies have shown that for parameters relevant to the atmosphere, at least two and more typically three or four states can be attained at large times depending on the initial conditions.

Numerical algorithms for implementing an Empirical Orthogonal Function (EOF) analysis of the high resolution numerical results were completed. The numerical model requires of order 64^2 spectral modes in each layer. These are linear Fourier harmonics. Low-order (e.g. 8x8) Fourier truncations don't even get the transition to chaos right! However, the EOF method is successful at replicating many of the high resolution complex simulations by obtaining low order descriptions based on the *nonlinear* orthogonal functions appropriate to the coherent structures in the original PDE calculations. Some of our 10^4 degree of freedom spectral numerical simulations can be reproduced by as few as 6 nonlinear ordinary differential equations for the amplitudes of the coherent structures. This method of reduction of a set of PDE's to a small number of ODE's provides a useful interpretive tool as well as an efficient predictive method. It provides a method for studying more complicated problems of climatic interest, including the effects of seasonal forcing on the level of internal variability and on the long-time evolution of model systems including nonlinear baroclinic wave transports.

COLUMNAR CONVECTION

Under conditions of rapid rotation and relatively low differential heating, convection in a spherical shell takes place as columnar "banana cells" wrapped around the annular gap, but with axes oriented along the axis of rotation. These were clearly evident in the GFFC experiments. Because the cells are aligned with the rotation axis, the simplest models for understanding their dynamics can be two-dimensional. There has been much recent effort to understand this type of 2-D convection. For example, Lin Busse and Ghil (GAFD, 45, 1989) use a spectral truncated low-order model to map out speculations about the transition to chaos. Lin (GAFD, 54, 1990) produced a low order model that generates *strong zonal banding* through the Reynolds stress associated with thermal convection in the presence of shear. This claim, which is offered as a mechanism for the banding on the giant planets, is in much dispute! Such bands were not seen in GFFC, although the parameters were different from those used by Lin. In an effort to resolve this dispute, a very accurate 2-D numerical model with resolution approaching 1024^2, was constructed. This model reproduces the GFFC results qualitatively. When extended to the cases studied by Lin no "double column instability" was found. The zonal flows were relatively weak.

Our recent numerical simulations of columnar convection contain several interesting results. First, the symmetry arguments of Cattaneo and Hart apply equally to this system, so there are at least two

independent *multiple states*. Indeed two of these were found numerically and their bifurcation trees (i.e. the transition to chaos) are being studied. The sideband instability of Lin et. al. does arise, though not at their truncated model's parameter values. Long waves propagate through the columns. In the chaotic states these intermittently organize the convection into larger vortex patches. This process may be related to the tendency for 2-D geostrophic turbulence to produce large isolated vortical structures, possibly leading to a strong zonal acceleration, a question that is still under study.

RESEARCH PLANS

We wish to further investigate nonlinear baroclinic flows. The initial success of the EOF method in producing a robust low-order system suggests an attempt to answer the following question. Under what circumstances can high resolution model results or laboratory data be represented by a low-dimensional model based on empirically determined nonlinear structures? What are the errors involved, data requirements, etc. Once a low order description is found, how can the low order structures be interpreted physically and perhaps arrived at beforehand from first principles?

These ideas shall be applied to the columnar (banana cell) convection models of circulation in the giant planets as well as to baroclinic instability. In both problems we shall pursue further the numerical simulations of transition to chaos, fractal behavior, and effects of additional realistic physical processes like time dependent forcing and small scale boundary layer turbulence on these processes. For example the transition to chaos and the nature of turbulent flow is strongly affected by the addition of a small amount of seasonal forcing. The dynamic origions of these effects are associated with the periodic forcing causing the system to locally approach homoclinic trajectories of the various invariant spectral manifolds in the system. A theory based on this idea, to be developed and verified by fully resolved numerical experiments, may lead to a better understanding of chaotic baroclinic wave systems.

RECENT PUBLICATIONS WITH NASA SUPPORT

Brummell, N., and Hart, J.E., "Numerical models of columnar convection" in preparation, 1991.

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Cattaneo, F., Brummell, N.H., Toomre, J., Malagoli, A, and Hurlburt, N.E., "Turbulent compressible convection" *Astrophysical J.*, **370**, 282-294, 1991.

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